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SMOKE PLUME TRAJECTORY FROM IN SITU BURNING OF CRUDE OIL IN ALASKA

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ABSTRACT

Experimentation, analysis and modeling have been performed to predict the downwind dispersion of smoke resulting from *in situ* burning of oil spills in Alaska. Laboratory burns of North Slope and Cook Inlet crude oils as well as mesoscale experiments performed at the U.S. Coast Guard Fire and Safety Test Detachment in Mobile, Alabama have provided input data for the LES (Large Eddy Simulation) plume trajectory model. A number of different fire sizes and weather conditions were considered with the aim of predicting the extent to which concentrations of smoke particulate matter would exceed ambient air quality standards. The model was also applied to the Newfoundland Offshore Burn Experiment (NOBE), where a comparison has been made between the model prediction and measurements of the smoke plume taken from an aircraft.

INTRODUCTION

A principal concern in the decision to use *in situ* burning as an oil spill mitigation technique is the anticipated trajectory of the smoke plume and the dispersion of the particulate matter generated by the fire. This paper describes the application of the Large Eddy Simulation (LES) model of smoke transport to a series of hypothetical *in situ* burns in Alaskan waters. This study was intended to predict the downwind extent of potentially dangerous levels of smoke under a number of different meteorological conditions. The model has also been used to make some comparisons to data collected from an aircraft during the Newfoundland Offshore Burn Experiment (NOBE).

Following is a brief description of the LES model. Further details may be found in References [1], [2] and [3]. The model consists of the conservation equations of mass, momentum and energy which describe the steady-state, convective transport of heated gases introduced into the atmosphere by a steadily burning fire and blown by a uniform ambient wind. The fire itself is not modeled, but rather the plume of smoke which emanates from it. Only the heat release rate and smoke yield of the fuel are required from experiments. The local meteorological conditions which must be provided are the wind speed, the fluctuation in wind direction, and the temperature stratification of the atmosphere. This model differs from most of the atmospheric dispersion models in use today because it is a *deterministic* rather than an *empirical* model; that is, the approach taken is to solve the governing equations of motion directly rather than relying on empirical formulae which approximate the extent of the dispersion. These empirical models typically assume the pollutant of interest to be Gaussian distributed in the plane perpendicular to the direction of the prevailing wind. The parameters defining the distribution are estimated from experiments. Unfortunately, the problem of *in situ* burning of crude oil is inappropriate for these types of models for two reasons: (1) The nature of the "source" is different than what is normally assumed, a smokestack, and (2) the size of the source is well beyond those considered in industrial applications and thus outside of the experimental parameter range.

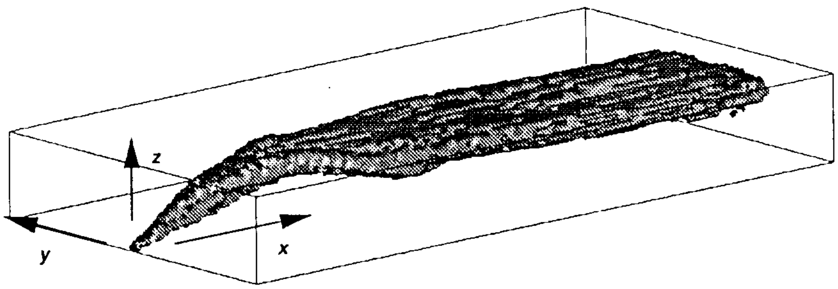

Figure 1: Three dimensional view of a computed smoke plume in the first few kilometers of its development. The height of the viewbox is 1 kilometer, the length 8 kilometers, and the crosswind length 4 km. The wind speed is 6 m/s. The computation is initialized by prescribing the temperature and particulate distribution in the plane spanned by the y and z coordinates. Then the plume is constructed as the initial plane is swept downwind.

Figure 1 displays the results of a typical LES model calculation. Shown is the surface which defines the outer extent of the plume, *i.e.* where the particulate concentration drops off to zero. References [1] and [3] contain details about the scaling and numerical solution of the governing equations. The main idea is that the three-dimensional, steady state set of conservation equations which govern the plume transport can be considered as a two-dimensional, time-dependent system by replacing the downwind spatial coordinate with a pseudo-temporal coordinate. The result is an initial value problem in which the solution is initially prescribed in a plane perpendicular to the direction of the prevailing wind. This initial plane is taken to be a few fire diameters downwind of the fire. Since the details of the fire are not simulated, the only information about the fire required is the overall convective heat release rate and the particulate mass flux. The particulate matter is represented by Lagrangian particles which are advected with the flow.

Atmospheric turbulence effects mixing on a wide range of scales, extending to scales which are smaller than the resolution of the calculations performed here. The small scale mixing is represented in the governing equations by a constant eddy viscosity, which is taken to be three orders of magnitude greater than the actual viscosity of air. The choice is governed by the desire for resolution limits in the five to fifteen meter range which are needed to capture the large scale fire-induced eddy motions. This requirement, together with the knowledge that the dissipative effects operate at length scales which are of the order of the overall geometric scale divided by the square root of the Reynolds number, yields Reynolds numbers of order 10^4. For this problem, the geometric scale is the stabilization height of the plume. However, the magnitude of the diffusive terms in the governing equations do not account for large scale atmospheric motion, such as the random shifting of the wind direction over the length and time scales considered, which may be tens of kilometers and a few hours, respectively. These wind fluctuations can be measured, and are introduced into the model as random perturbations to the trajectories of the Lagrangian particles which represent the particulate matter. Details of this procedure may be found in Reference [2].

IN SITU BURNING IN ALASKA

The LES model was applied to a series of hypothetical burns in Alaska. Details of the study may be found in Reference [2]. Briefly, laboratory-scale experiments were conducted to determine the heat release rate and smoke yield from two types of Alaskan crude oils, North Slope and Cook Inlet, burning in a 1.2 meter diameter pan. Based on results from mesoscale experiments performed in a 15 meter square pan at the U.S. Coast Guard mesoscale burn facility in Mobile Bay, Alabama, the laboratory results for the Alaskan crude oils were extrapolated to mesoscale to be used as input for the LES plume trajectory model. The scenario of interest is the burning of crude oil in the confines of a boom in the waters off the coast of Alaska. Various fire sizes were considered, ranging from 400 to 1800 MW. Smoke yields were estimated at 9.2% for Cook Inlet crude and 11.6% for North Slope crude. A number of different meteorological conditions were also considered, corresponding to either the southern or northern coasts of Alaska in either the summer or winter.

A sample calculation for a hypothetical *in situ* burn is presented in Figure 2. In the upper left hand corner of the figure is a typical temperature profile for the Cook Inlet region in the winter. The effect of the temperature inversion on the plume rise is evident in the plot of the plume cross-section in the upper right hand corner which shows the crosswind extent of hour-averaged plume particulate concentrations of 50, 150 and 300 $\mu g/m^3$, 5 kilometers downwind of the burn site. A similar plot below it shows the downwind extent of these concentration levels. Next, the shaded plot displays the concentrations at the ground level. The term "ground level" refers to the first 5 to 10 meters of the atmosphere, reflecting the resolution of the finite difference approximation of the governing equations. Finally, the plot at the bottom of the figure is included to partially quantify the previous contour plot. It shows the decrease in the ground concentration along the plume centerline.

It should be noted that the scenario described in the sample calculation represents unfavorable burn conditions; that is, there is a fairly severe temperature inversion and strong winds. The focus of effort was on such unfavorable conditions so as to build in a factor of safety which accounts for the many uncertainties of the model. Indeed, for more typical daytime conditions, the model would predict virtually no mixing of particulate matter to the ground level in the absence of any major terrain or meteorological effect which is not accounted for by the model.

The heat release rates and the smoke yields for the two types of oil considered were similar and did not dramatically change the results of the computations. The North Slope crude had a lower heat release rate and a higher particulate yield, thus its burning produced a slightly less elevated plume with higher particulate concentrations than that produced from the burning of Cook Inlet crude. Given the assumptions and simplifications inherent in the model, this small difference in crude oil properties was of little consequence to the ultimate objective of the study, which was to predict

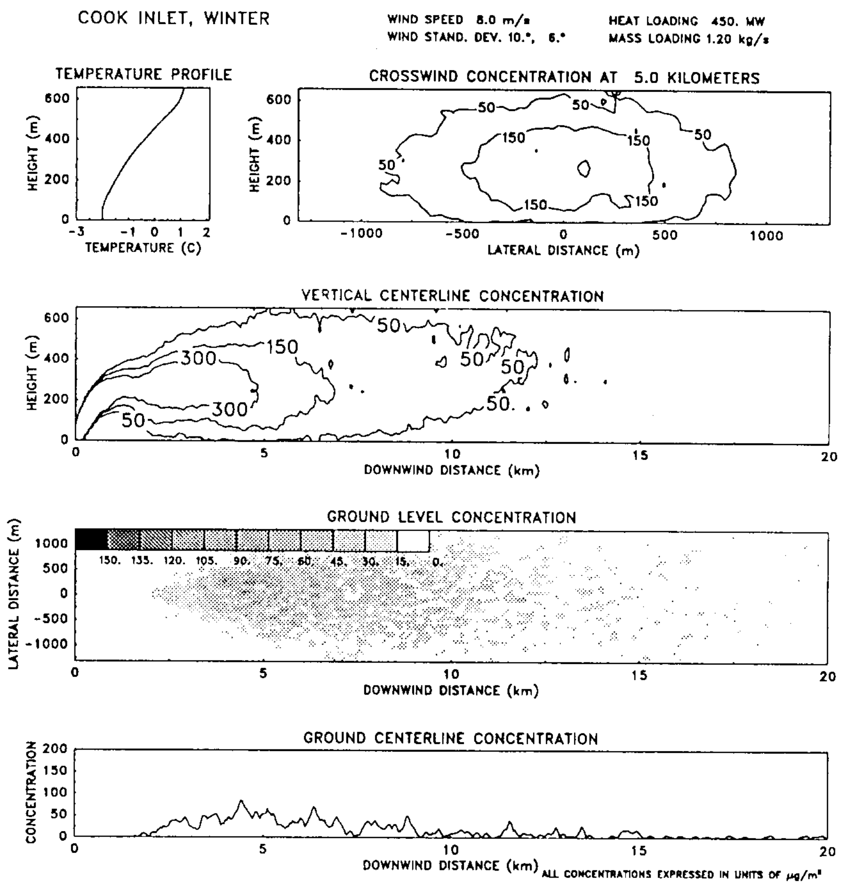

Figure 2: Sample results for a typical LES plume model run. This case considers the burning of Cook Inlet crude oil in the vicinity of the Cook Inlet. All concentrations are expressed in units of $\mu g/m^3$. Wind Stand. Dev. expresses the lateral and vertical standard deviations to the mean wind direction, averaged over approximately one hour. Heat Loading refers to the *convective* heat release rate. Mass Loading refers to the particulate mass production rate.

the downwind and lateral extent of harmful concentrations of particulate matter. A particulate concentration in excess of 150 $\mu g/m^3$ averaged over one hour was chosen as an appropriate level of concern. It was found after running a number of cases with different meteorological conditions and various burn sizes that this level of particulate matter was not expected beyond about five kilometers downwind of the burn nor outside a path of about a kilometer in width. Indeed, in most cases these levels were not expected beyond one kilometer downwind, but a reasonable level of caution is advised in interpreting the results from any model.

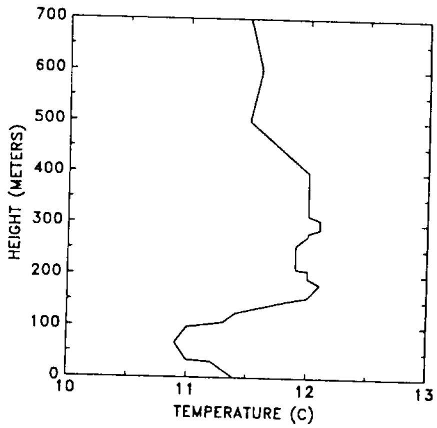

Figure 3: Atmospheric temperature profile for the second NOBE burn used in the model simulation. The profile is based on measurements taken by the NIST tethered blimp (< 320 m) [4] and University of Washington aircraft (> 320 m) [6].

THE NEWFOUNDLAND EXPERIMENT

The Newfoundland Offshore Burn Experiment (NOBE) has provided data with which to compare the results of the model. Dr. Ron Ferek of the University of Washington's Cloud and Aerosol Research Group led a team of scientists in performing airborne measurements of the emission from two *in situ* burns of crude oil conducted off the coast of St. John's, Newfoundland on August 12, 1993. More data is available for the second burn, so that one will be used for the comparison. For this burn, it was reported that 28.9 m^3 of crude oil of density 843.7 kg/m^3 was burned in 1.3 hours [7]. For the purposes of modeling the plume, it was assumed that the burning rate was constant at 5.2 kg/s. Based on previous work with Louisiana crude [1], the effective heat of combustion of the oil was assumed to be 42,000 kJ/kg, even though a different oil was used for the tests. The smoke yield for the burn was measured by the team from the National Institute of Standards and Technology (NIST) to be approximately 15% [4], and the fraction of the total heat release lost as radiation was assumed to be 10% [5]. Thus, the *convective* heat release rate for the model run was about 200 MW and the particulate production rate was 0.78 kg/s. Temperature soundings taken from the University of Washington aircraft [6] and from the NIST tethered blimp [4] indicate

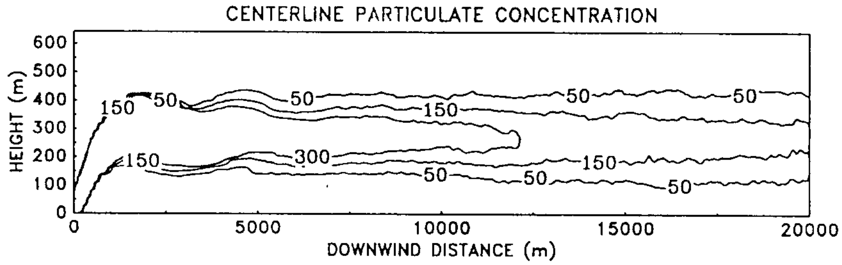

Figure 4: Centerline particulate concentration of the computed smoke plume of the second NOBE burn. Concentrations are expressed in units of $\mu g/m^3$.

that the temperature profile of the first few hundred meters of the atmosphere showed an inversion (see Figure 3). The wind speed at the ground was about 5 to 6 m/s, increasing to about 8 m/s a few hundred meters up. This was accompanied by a shift of roughly 30 to 40° in the direction of the wind. To account for the wind fluctuations, and to some extent the wind shear, the lateral angular standard deviation was assumed to be 6°, the vertical 1°. The fact that the model can only accommodate small perturbations to the prevailing wind direction makes modeling the wind shear difficult. A needed improvement to the model is a better consideration of wind shear.

The computed plume trajectory is shown in Figure 4. Cross sectional slices are shown in Figure 5. There is quite a difference between the plume trajectories shown in Figures 2 and 4. The main reason for the difference is the designation of the wind fluctuations. The scenario of interest for the Alaska simulations was the transport over land of a smoke plume originating over water. Wind fluctuations are generally greater over land due to terrain and surface convection effects. This leads to more rapid dispersion of plume constituents, but a greater possibility of mixing to the ground. Over water, wind fluctuations are less severe, giving rise to plumes which remain intact (*i.e.* visible) for tens of kilometers and never mixing to the surface. This was the case in Newfoundland, according to those on board the test aircraft [6]. LIDAR measurements taken from the aircraft show the centerline of the plume rising to a height of about 300 m, leveling off for about 5 km, and then gradually rising to a height of about 600 m after 20 km. The centerline of the computed plume reached a height of about 300 m, but does not show this gradual rise. It is unclear exactly why it occurs. It has been speculated that this lofting might be due to the heat generated by the absorption of sunlight by the dark plume. Another explanation might be that the temperature of the atmosphere decreased sufficiently fast above the inversion layer to allow for additional lofting. However, the temperature profiles taken from the aircraft do not show a significant temperature decrease above the inversion layer.

Plume particulate concentrations may be derived either by converting the LIDAR cross section data to mass, or by measuring the excess CO_2 and backing out the particulate concentration based on the smoke yield and the elemental carbon mass fraction of the fuel. The conversion of the LIDAR data is still underway and will be presented elsewhere. Instead, direct measurements of excess CO_2 made while flying the aircraft along the centerline of the plume have been used to estimate the concentration

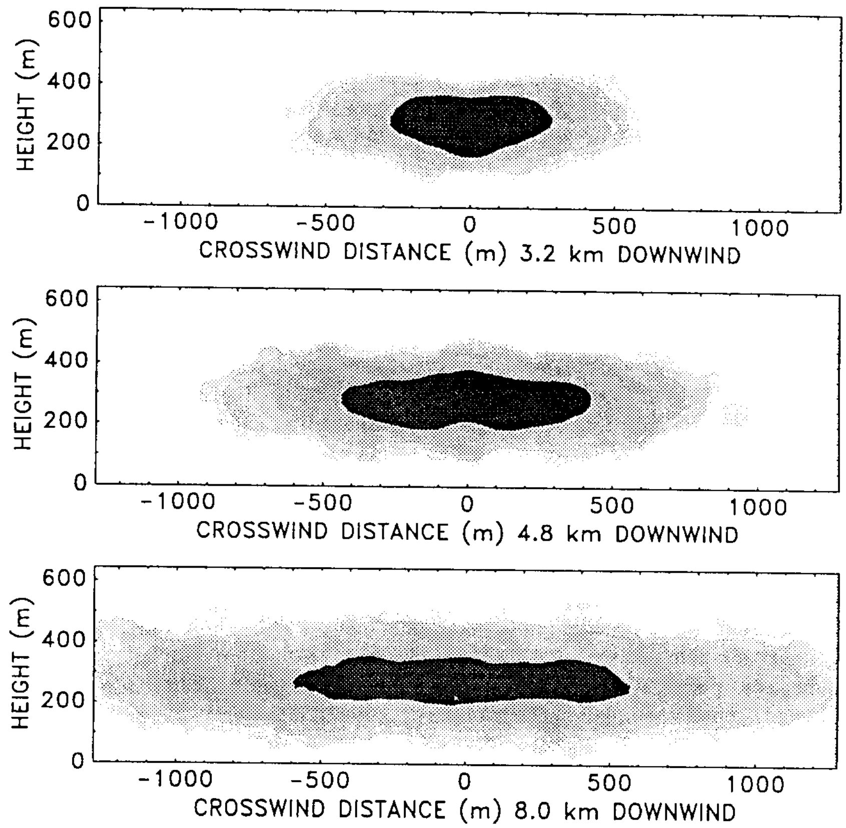

Figure 5: Cross sectional slices of the computed smoke plume from the second NOBE burn. The darker area show particulate concentrations in excess of 150 $\mu g/m^3$.

of particulate matter. In deriving the concentration from the measured volume fraction of excess CO_2, it was assumed that the smoke yield was 15% and the elemental carbon mass fraction of the fuel was 0.8664; and the result is that 1 ppm excess CO_2 corresponds to a particulate concentration of 103 $\mu g/m^3$. Direct measurements of excess CO_2 by Ferek found volume fractions decreasing to about 1.5 ppm (the equivalent of 150 $\mu g/m^3$ particulate) by about 16 km downwind of the burn. The model calculation predicts that concentrations in excess of 150 $\mu g/m^3$ extend slightly farther than 20 km downwind. The discrepancy in the two estimates is not surprising, given the enhanced plume dispersion of the experiment due to wind shear and lofting. Also, the comparison is being made based on only one pass of the aircraft along the plume centerline, which may not account for the maximum concentration. Indeed, the model predicts and visual sightings confirm the existence of counter-rotating vortices which are generated by the fire and which entrain a substantial fraction of the particulate. Thus, it is not necessarily true that the maximum concentration of particulate would be found along the centerline of the plume. *In situ* measurements of the plume cannot account for its complex structure, and thus a better means of measuring particulate concentration would be through the use of integrated techniques. Hopefully the analysis of the LIDAR data which has yet to be completed should confirm some of the results which are based on *in situ* measurements of excess CO_2.

CONCLUSION

The Large Eddy Simulation plume trajectory model has proven to be a very useful tool in determining the structure and extent of smoke plumes from *in situ* burns. With the increased computing power of moderately-priced workstations (and eventually the next generation of personal computers), it is relatively easy to consider a wide range of burn scenarios, such as those considered in the Alaska study. Those simulations were performed on an IBM RISC/6000 (model 550) workstation, and typical run times were on the order of 10 to 15 minutes, with a memory requirement of about 30 megabytes. Short run times are an important consideration because of the wide range of meteorological parameters that must be studied to yield confidence in the final prediction.

However, the comparison of the model prediction with the observations of the NOBE burn shows that despite the reasonably high resolution of the calculations, uncertainties need to be recognized. These uncertainties arise from two sources: (1) assumptions of the model, and (2) lack of information about meteorological conditions. For example, the assumption that the wind speed and direction are uniform with height leads to the neglect of wind shear, which can be an important agent of plume dispersion. The steady-state assumption neglects unsteady burning rates which can affect the plume dynamics. The selection of eddy viscosity and wind fluctuation values is difficult due to the uncertainty involved in quantifying atmospheric turbulence. Often the data necessary to select appropriate values cannot be obtained, and empirical estimates must be used. Despite all these difficulties, the continued application of the model to various burn scenarios leads to a better understanding of trends and phenomena which instill confidence in the overall methodology. Continued experimental verification will be sought to confirm the quantitative predictions of the model, and continued improvements to the model will be made to address issues which arise from attempts to predict plume trajectories from actual *in situ* burns.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Walton, W.D. *et al.*, "*In-Situ* Burning of Oil Spills: Mesoscale Experiments and Analysis", Proceedings of the Sixteenth Arctic and Marine Oil Spill Program Technical Seminar, June 7–9, 1993, Calgary, Alberta, pp. 679–734.

[2] McGrattan, K.B., Putorti, A.D., Twilley, W.H., and Evans, D.D., "Smoke Plume Trajectory of *In Situ* burning of Crude Oil in Alaska", NISTIR 5273, National Institute of Standards and Technology, Gaithersburg, Maryland, 20899, October 1993.

[3] Baum, H.R., McGrattan, K.B. and Rehm, R.G., "Simulation of Smoke Plumes from Large Pool Fires", to be presented at the 25th International Symposium on Combustion, University of California, Irvine, July 31–August 5, 1994, and published in the conference Proceedings.

[4] Walton, W.D., Twilley, W.H., McElroy, J., Evans, D.D., and Tennyson, E.J., "Smoke Measurements Using a Tethered Miniblimp at the Newfoundland Offshore Oil Burn Experiment", Proceedings of the Seventeenth Arctic and Marine Oil Spill Program Technical Seminar, June 8–10, Vancouver, British Columbia.

[5] Koseki, H. and Yumoto, T., "Air Entrainment and Thermal Radiation from Heptane Pool Fires", Fire Technology, February, 1988.

[6] Ferek, R., private communication.

[7] "NOBE Facts" newsletter, Vol. 6, Newfoundland Offshore Burn Experiment Committee, Ottawa, Ontario, January, 1994.